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Surface-tension driven self-assembly of microchips on hydrophobic receptor sites with water using forced wetting

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This letter reports water droplet self-alignment methods for self-assembly of microchips on hydrophobic receptor sites in ambient air environment. It is an open question if lyophobic receptor site of the self-alignment medium can be used for self-assembly. We investigate this question using both numerical simulation and experimental studies on hydrophobic receptor sites (advancing contact angle of 118°) with superhydrophobic substrate (contact angle of 180°). We demonstrate that self-alignment is possible using two forced wetting methods: (a) introducing an excessive amount of water and (b) applying external pressure. The results suggest that surface-tension driven self-alignment can be applied in a wider combination of materials and mediums. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4751980]

Surface-tension driven self-assembly and hybrid-assembly of microchips is a topic attracted wide interests.[1–15] One key aspect of the technology is a well-designed receptor site where the self-alignment process of the self-assembly will take place. The general rule is that the receptor site should be lyophilic (against the lyophobic background) to the self-alignment medium—the liquid medium between the receptor site and the micropart to be assembled, e.g., hydrophilic receptor site if water is used as the self-alignment medium in air[6–11] or oleophilic receptor site if adhesive is used as self-alignment medium in water.[1–5] In air, solid-edges can also be used as the boundary for the self-alignment process.[12,15] However, the general rule of a lyophilic receptor site still applies. It is largely an open question if lyophobic receptor site of the self-alignment medium can be used also for self-assembly. The answer of this question, if positive, will relax the fabrication requirements for self-assembly, which may significantly impact the applications.

In this letter, we investigate this question using both numerical simulation and experimental studies. We choose water droplet self-alignment as the test bench for its simplicity. The process includes a water droplet as the self-alignment medium, a hydrophilic chip, a hydrophobic receptor site, and a super hydrophobic substrate.

The problems of water droplet self-alignment using hydrophobic receptor sites are illustrated using a numerical program Surface Evolver[16] in Fig. 1. The volume of droplet is 0.9 nl which is typical for the size of the chip and the receptor site ($200\,\mu m \times 200\,\mu m$).[8] In the case of hydrophobic receptor site as shown in Figs. 1(a1)–1(a4), a chip is released above a hydrophobic receptor site where a droplet of water lies, and a meniscus is formed between the chip and the receptor site (Fig. 1(a1)); the shape of the meniscus generated a so-called restoring force that moves the chip towards the receptor site to minimize the total surface energy of the meniscus (Figs. 1(a2) and 1(a3)); finally, the chip stops at the location where the surface energy of meniscus is minimized and the water evaporates (Fig. 1(a4)). Figs. 1(b1)–1(b4) and 1(c1)–1(c4) demonstrate experimentally that there is a large un-wetted area on receptor site at each step of the process (top view in Figs. 1(b1)–1(b4) and side view in Figs. 1(c1)–1(c4)) and an obvious final misalignment (translational error of 38 μm in x-axis, 1.5 μm in y-axis, and rotational error of 12.5°). Fig. 1(d) shows the relation between surface energy of water meniscus and displacement of the chip on the hydrophobic receptor site against the same process on a hydrophilic receptor of contact angle of 30°. The blue curve in Fig. 1(d) indicates the water meniscus on hydrophobic receptor site has reached its equilibrium state when the translational misalignment is about 30 μm, where the energy curve (Fig. 1(d)) is flattened and the restoring force is approaching zero (Fig. 1(e)). This is dramatically different from the case with hydrophilic receptor site. Consequently, the chip stops moving before it reaches the target position. Furthermore, the restoring force is much smaller (Fig. 1(e)) than on the hydrophilic receptor site, which makes the self-alignment process more sensitive to disturbance. The small amount of noise appearing in the restoring force curve (red curve) of Fig. 1(e) is due to the numerical errors in simulation, which, however, does not affect the estimation of the level and trend of the force.

To tackle the problems of poor wetting and low restoring force, we developed two forced wetting methods for self-alignment. Forced wetting is a technique mostly used in coating;[17] in this paper, we refer to the forced spreading of liquid on the receptor site beyond what can be achieved by the wetting of the normal amount of water used in self-alignment. The two methods are: (a) introduce an excessive amount of water than that is needed for self-alignment and (b) force the water droplet to wet the hydrophobic receptor sites by pushing the chip against the receptor site.

To experimentally study the problem, we use a nanostructured black silicon surface functionalized with fluoropolymer as a super-hydrophobic substrate,[18] while the silicon dioxide receptor sites covered with fluoropolymer serve as the hydrophobic receptor sites. Fig. 2 shows the fabricated receptor site and substrate. The height of the

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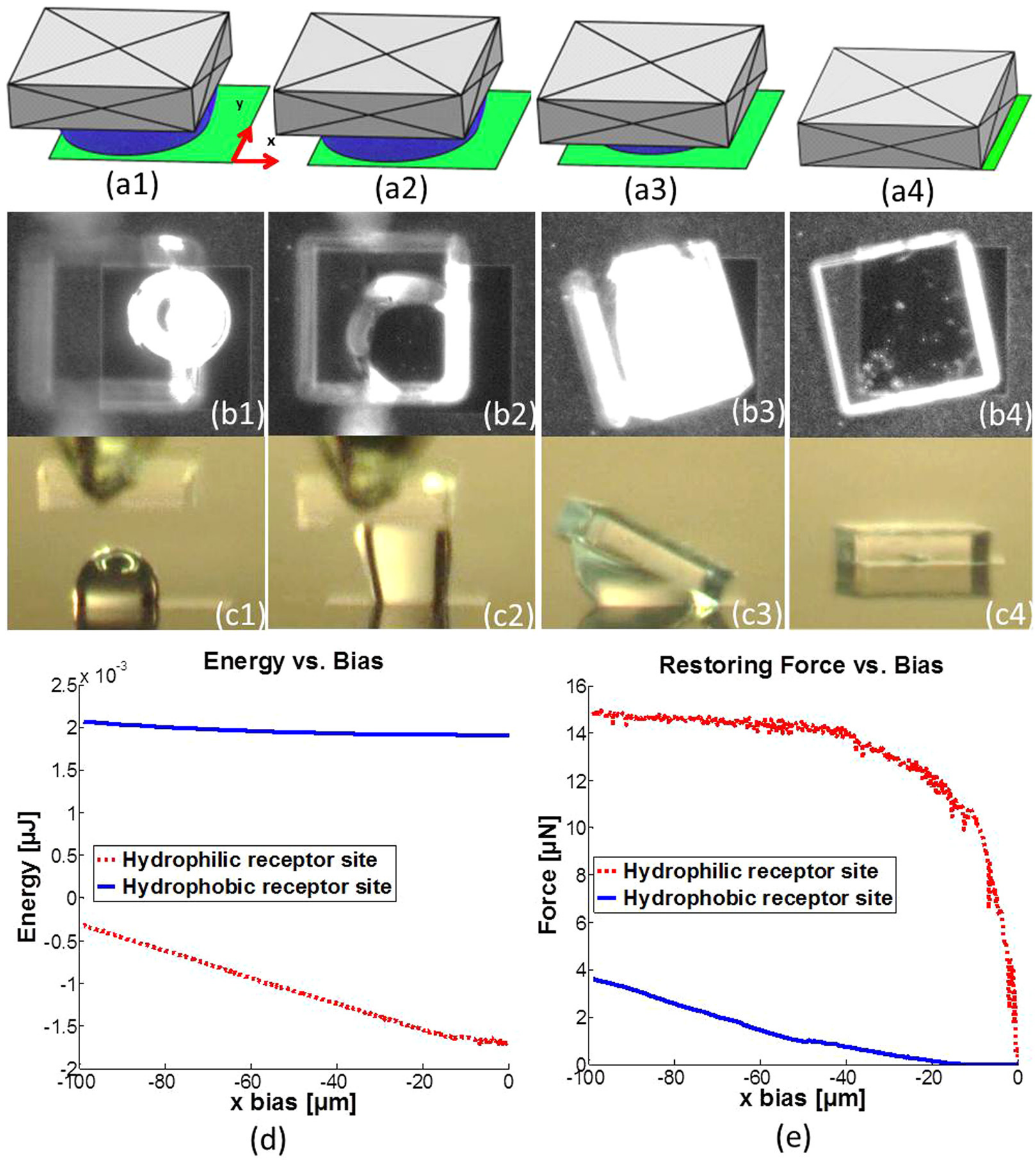

FIG. 1. Numerical simulation and experimental test of water droplet self-alignment of a microchip on a hydrophobic receptor site with volume of water: 0.9 nl, size of the chip and the receptor site: 200 μm $\times$ 200 μm and water contact angle of receptor site, substrate, and chip: 118°/180°/80°. (a1) A chip is above a receptor site with a droplet of water in middle; (a2) and (a3) the droplet minimizes its surface area and moves the chip towards the receptor site; and finally water evaporates and alignment is failed in (a4). (b1)–(b4) Video frames of droplet self-alignment from top view; (c1)–(c4) Video frames of the droplet self-alignment from side view; (d) energy curve, and (e) restoring force of the water meniscus.

fabricated receptor site is 3.4 μm as shown in Fig. 2(b). The contact angle of water on the substrate is 180° as shown in Fig. 2(c). The advancing and receding contact angles of the water are 118° and 69° correspondingly on the receptor site as shown in Figs. 2(d) and 2(e). Fig. 2(f) shows that the receptor site can effectively confine a large amount (about 29 nl) of water. The same material was used in the experiment of Figs. 1(b1)–1(c4).

Experimental tests have been carried out using 200 μm $\times$ 200 μm SU-8 chips on hydrophobic receptor sites with matching size and shape. SU-8 is an epoxy-based negative photoresist suitable to fabricate thick microstructures up to hundreds of micrometers using standard lithography.[19] The chips are picked and placed on the receptor sites using an automatic microhandling platform which includes a water droplet dispenser.[8] The tests were done in ambient room environment.

The first forced wetting technique enables the water drop pinning at the edges of the receptor sites (see Figs. 3(a1) and 3(b1)) by dispensing excessive amount of water on receptor site. Figs. 3(a) and 3(b) (top view: a1–a4 and side view: b1–b4) show the frames of the self-alignment processes for an assembly case of a 200 μm $\times$ 200 μm $\times$ 50 μm chip on a 200 μm $\times$ 200 μm receptor site using excessive amount of water (about 8 nl). Such large amount of water is sufficient to fully wet the surface of the receptor site, and moreover the water is still well confined inside the receptor site due to the edge effect and super-hydrophobic substrate. Reliable self-alignment has been observed using this technique. However, the self-alignment takes much longer time (around 5 s) than the time (half a second) for self-alignment with smaller amount of water (0.2–1.5 nl).[8] The long alignment duration is mainly caused by longer evaporation time for large amount of water. It has also been observed that the

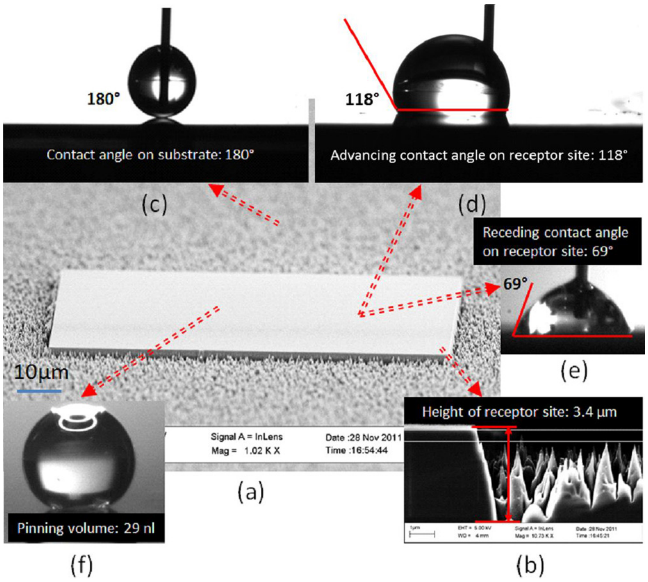

FIG. 2. Characteristic and wetting property of the fabricated receptor site and substrate: (a) a SEM image of a $200\,\mu m \times 200\,\mu m$ receptor site on the substrate; (b) the profile of the fabricated receptor site with height of $3.4\,\mu m$; (c) the advancing contact angle of water on substrate: 180°; (d) the advancing contact angle on the receptor site: 118°; (e) the receding contact angle on the receptor site: 69°; and (f) a large amount of water droplet (29 nl) is pinning at the edge of the receptor site due to the solid edges and super hydrophobicity of the substrate.

chip is tilted (Fig. 3(a3)) during the evaporation, which however does not affect the final self-alignment.

In order to speed up the alignment process, we have developed the second technique, which applies the normal amount (0.4–1.5 nl) of water for self-alignment, but the water drop is forced to spread on the hydrophobic receptor site by pushing the top chip against the receptor site. Figs. 3(c) and 3(d) (top view: c1–c4 and side view: d1–d4) show the frames of the self-alignment processes for an assembly case of a $200\,\mu m \times 200\,\mu m \times 50\,\mu m$ chip on a $200\,\mu m \times 200\,\mu m$ receptor site using the forced wetting technique. Small amount of water (about 0.9 nl) is dispensed on the receptor site, and the surface of the receptor site is partly wetted (Figs. 3(c1) and 3(d1)). The gripper pushes the chip against the receptor site and forces the water droplet to wet the receptor site (Figs. 3(c3) and 3(d3)). Then the chip is released, and the surface tension drives the chip to align with the receptor site (Figs. 3(c4) and 3(d4)). The wetted area on the receptor site is obviously greater than the case without pressing (Fig. 1(c3)). Similar tilting of the chip as the case of the first method has also been observed during the alignment process. The alignment process takes about 0.7 s. This technique provides a promising solution for applications where the alignment time is critical.

Both forced wetting techniques lead to greater wetting area of the receptor site and reliable self-alignment. Those results can also be theoretically explained. In the case with excessive amount of water, the chip should align with the receptor site due to the full wetting. During the vaporization of the water, self-alignment should be maintained because the contact angle will change from the advancing contact angle to the receding contact angle. Therefore, the restoring force of the later phase of the self-alignment process should be calculated based on the receding contact angle on receptor site instead of advancing contact angle and the force will be greater.

Figs. 3(e) and 3(f) compared the surface energy and restoring force of the self-alignment process of three cases with the same amount of water of 0.9 nl: on a hydrophilic receptor site, on a hydrophobic receptor site with either the receding contact angle or the advancing contact angle as the contact angle in simulation. Fig. 3(f) shows that the receding contact angle of 69° leads to much larger value of restoring force compare with the much smaller forces created using advancing contact angle. By using the receding contact angle as the contact angle in simulation, the Surface Evolver model indicates that perfect alignment can be achieved on hydrophobic receptor site when the receding contact angle is in action, in contrast to Figs. 1(a1)–1(b4). The restoring force in the real case should start with the blue curve simulated using advancing contact angle in Fig. 3(f) and shift to the black curve simulated using receding contact angle at the later phase of the self-alignment process. In the case of pressing, we believe that the much larger wetting also reduces the effective contact angle to a value close to the receding contact angle after the pressing was ended, and therefore the results of Figs. 3(e) and 3(f) should also apply. During the self-alignment process, the gravitational force can be neglected due to the size of the chip ($200\,\mu m$) is much smaller than the capillary length (2.7 mm) for clean water at standard temperature and pressure.

Multiple self-alignment tests were carried out to investigate the self-alignment accuracy on hydrophobic receptor sites with both excessive amount of water and external pressure. During the tests, the same initial biases ($60\,\mu m$ in x axis, $60\,\mu m$ in y axis, 49% overlapping area) were used repeatedly with SU-8 chips and receptor sites sizes of $200\,\mu m \times 200\,\mu m$. The alignment accuracy was calculated based on optical images by measuring the difference between the geometry centers of the SU-8 chips and the receptor sites after the self-alignment is realized. The alignment accuracy was measured for three cases: (1) self-alignment on hydrophobic receptors without forced wetting; (2) self-alignment on hydrophobic receptors with excessive amount of water; and (3) self-alignment on hydrophobic receptors with external pressure. In the first case, the self-alignment was totally failed on hydrophobic receptor sites without forced wetting, which leads to errors of tens to hundreds of micrometers. In the second case, the root mean square (RMS) of the accuracy was estimated as $1.3\,\mu m$ in x-axis and $2.8\,\mu m$ in y-axis on hydrophobic receptor site with excessive amount of water. Similar alignment accuracy of $1.7\,\mu m$ in x-axis and $2.3\,\mu m$ in y-axis was achieved for hydrophobic receptor sites with external pressure. The accuracy in both second and third cases is as good as the manufacturing precision of the chip, which is in the range of 1 to $2\,\mu m$. The alignment accuracy is also in the same range as the results for similar sized hydrophilic receptor sites, which is around $2\,\mu m$.[8] Using manufacturing process with higher precision, sub-micrometer accuracy should be possible.[20]

In summary, we have demonstrated that self-alignment is possible on a hydrophobic receptor site with super-

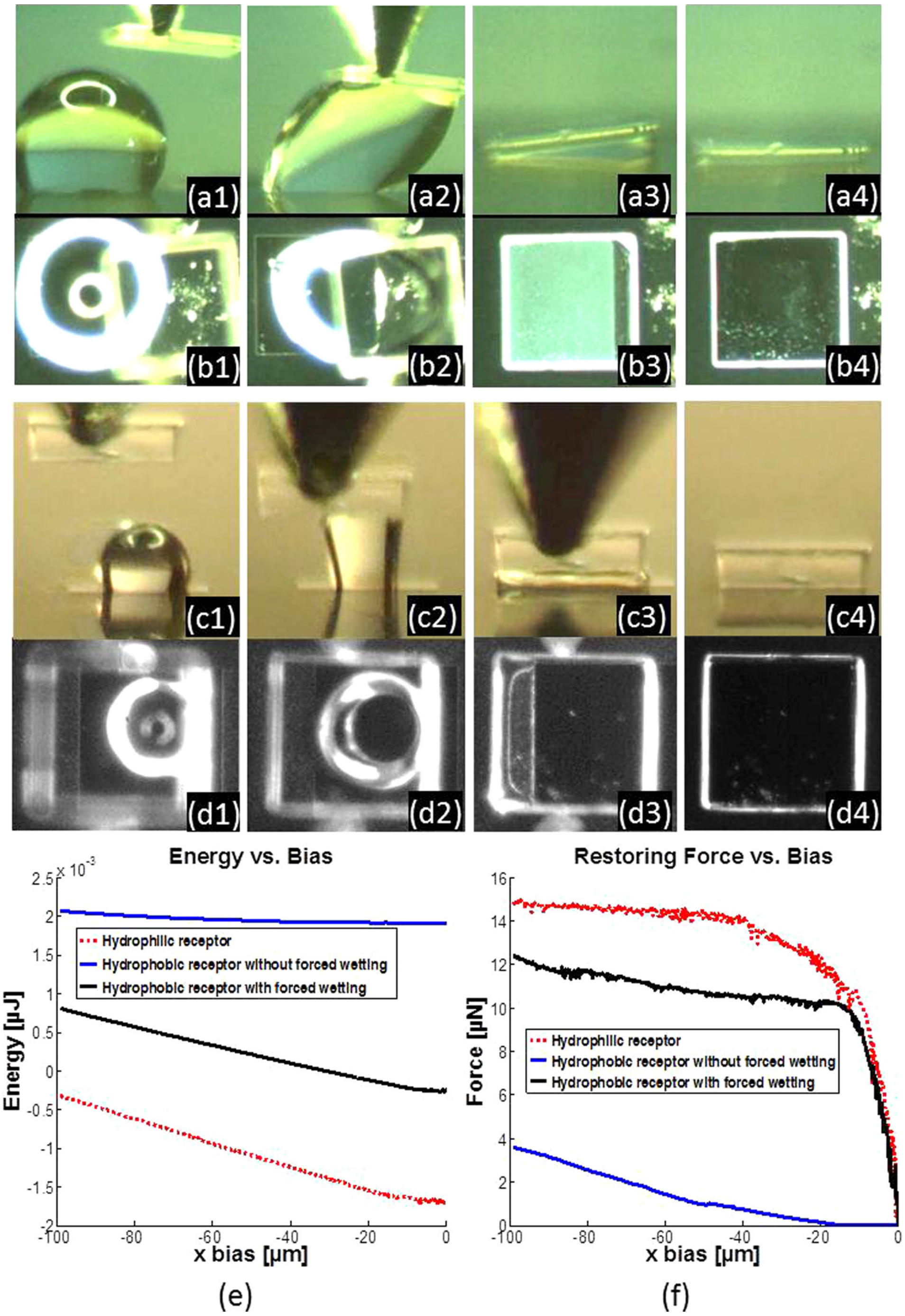

FIG. 3. Experimental tests and numerical simulation of water droplet self-alignment of a microchip on a hydrophobic receptor site with forced wetting, with volume of water 0.9 nl, size of chip and hydrophobic receptor site 200 μm × 200 μm, advancing contact angle and receding contact angle of water on receptor site 118° and 69°, respectively: (a1)–(a4) and (b1)–(b4) top view and side view of drop self-alignment with excessive amount of water (8 nl); (c1)–(c4) and (d1)–(d4) top view and side view of drop self-alignment applying external pressure to force the water to wet the hydrophobic receptor site; (e) and (f) energy and restoring forces on hydrophilic receptor, hydrophobic receptor with forced wetting, and hydrophobic receptor without forced wetting (enhanced online) [URL: http://dx.doi.org/10.1063/1.4751980.1], [URL: http://dx.doi.org/10.1063/1.4751980.2].

hydrophobic substrate using forced wetting, by either introducing an excessive amount of water or applying external pressure to force the water to wet the hydrophobic receptor sites. This may relax the requirement in some potential applications in packaging of semiconductor devices and 3D integration of the micro devices, where the surfaces of the receptor sites could be hydrophobic.

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